

CLAIMS

1. A method of resampling medical imaging data from a first spatial distribution of data points onto a second spatial distribution of data points, comprising:
 - 5 determining a matrix of reverse interpolation coefficients for resampling data from said second spatial distribution onto said first spatial distribution;
 - inverting a matrix based on said reverse interpolation matrix to determine forward resampling coefficients for resampling data from said first spatial distribution to said second spatial distribution; and
 - 10 resampling data from said first spatial distribution onto said second spatial distribution using said forward resampling coefficients.
2. A method according to claim 1, wherein inverting the matrix based on said reverse interpolation matrix comprises inverting the reverse interpolation matrix.
- 15 3. A method according to claim 1, wherein the matrix based on the reverse interpolation matrix comprises the sum of the reverse interpolation matrix multiplied by its Hermitian conjugate and a parameter matrix.
- 20 4. A method according to claim 3, wherein the parameter matrix comprises a diagonal matrix.
5. A method according to claim 3 or claim 4, wherein all the non-zero elements of the parameter matrix are substantially equal.
- 25 6. A method according to any of claims 3-5, wherein the parameter matrix comprises a correlation matrix.
7. A method according to any of claims 1-6, wherein the resampling coefficients comprise interpolation coefficients.
- 30 8. A method according to any of claims 1-6, wherein the resampling coefficients comprise estimation coefficients.

9. A method according to any of claims 1-8, wherein determining the reverse interpolation matrix comprises determining a real matrix.
- 5 10. A method according to any of claims 1-9, wherein said second spatial distribution comprises a uniform spatial distribution.
11. A method according to claim 10, wherein said first spatial distribution comprises a non-uniform spatial distribution.
- 10 12. A method according to claim 10, wherein said second spatial distribution comprises a radial spatial distribution.
13. A method according to claim 10, wherein said second spatial distribution comprises a
15 Cartesian spatial distribution.
14. A method according to any of claims 1-13, wherein said medical imaging data comprises Magnetic Resonance k-space data.
- 20 15. A method according to claim 14, wherein said medical imaging data comprises Magnetic Resonance imaging data.
16. A method according to claim 14, wherein said medical imaging data comprises Magnetic Resonance spectroscopy data.
- 25 17. A method according to any of claims 1-13, wherein said medical imaging data comprises CT k-space data.
18. A method according to any of claims 1-13, wherein said medical imaging data
30 comprises CT projection data, converted from fan-beam to parallel beam.
19. A method according to any of claims 1-13, wherein said medical imaging data comprises diffraction tomography k-space data.

20. A method according to any of claims 1-19, wherein inverting comprises calculating a pseudo-inverse matrix.

5 21. A method according to claim 20, wherein inverting comprises inverting using rank truncated SVD (Singular Value Decomposition).

22. A method according to any of claims 1-21, wherein said determining is performed locally on said first and second spatial distributions.

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23. A method according to claim 22, wherein said inverting is performed locally on said first and second spatial distributions.

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24. A method according to claim 23, wherein determining a matrix of resampling coefficients comprises selecting \bar{M} points from said second spatial distribution and \bar{N} points from said first spatial distribution, for each of said localities.

25. A method according to claim 24, wherein said \bar{M} points are selected from a first region surrounding a point x_i .

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26. A method according to claim 25, wherein \bar{M} is dependent on the locality.

27. A method according to claim 25 or claim 26, wherein said first region is circular, having a first radius dependent on the locality.

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28. A method according to claim 25 or claim 26, wherein said first region is non-circular.

29. A method according to claim 28, wherein said first region is rectangular.

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30. A method according to any of claims 24-29, wherein said \bar{N} points are selected from a second region surrounding a point x_i .

31. A method according to claim 30, wherein \bar{N} is dependent on the locality.

32. A method according to claim 30 or 31, wherein said second region is circular, having a second radius dependent on the locality.

5 33. A method according to claim 30 or 31, wherein said second region is non-circular.

34. A method according to claim 33, wherein said second region is rectangular.

10 35. A method according to any of claims 23-34, wherein said resampling comprises generating an inversion matrix wherein each row is created from an inversion at a locality.

36. A method according to claim 35, comprising copying resampling coefficients resulting from said inversion into a zeroed matrix row of said inversion matrix, which row corresponds to point x_i .

15 37. A method according to any of claims 23-36, wherein said determining is performed using a grid different from said second spatial distribution.

20 38. A method according to claim 37, wherein said different grid has a greater extent than said second spatial distribution.

39. A method according to claim 37 or claim 38, wherein said different grid has a different spacing than said second spatial distribution.

25 40. A method according to claim 39, wherein said different grid has a larger spacing than said second spatial distribution.

41. A method according to claim 39, wherein said different grid has a smaller spacing than said second spatial distribution.

30 42. A method according to any of claims 23-41, wherein said resampling comprises pre-multiplying a matrix comprising said forward interpolation coefficients, by a filter.

43. A method according to claim 42, wherein said filter has a FIR (Finite Impulse Response) and wherein said FIR is smaller than an extent of said locality.
44. A method according to claim 42 or claim 43, wherein said filter has an impulse response having most of its energy concentrated within an area smaller than an extent of said locality.
45. A method according to any of the preceding claims, wherein said resampling comprises resampling spatial data having dimensionality greater than one.
46. A method according to any of the preceding claims, comprising reconstructing an image from said resampled data by applying an FFT (Fast Fourier Transform) to said data.
47. A method of resampling comprising:
providing data in a first spatial distribution of data points;
providing a second spatial distribution of data points; and
resampling data from said first spatial distribution onto said second spatial distribution, without generating artifacts in the data, which artifacts could be corrected by pixel-by-pixel multiplying an image reconstructed from said resampled data, by a pre-determined post-compensation matrix,
wherein said resampling is performed by multiplying said data by a single matrix.
48. A method according to claim 47, wherein said single matrix is a sparse matrix in which each row comprises at least 20% zero elements.
49. A method according to claim 48, wherein said single matrix is a sparse matrix in which each row comprises at least 50% zero elements.
50. A method according to claim 49, wherein said single matrix is a sparse matrix in which each row comprises at least 80% zero elements.
51. A method according to any of claims 47-50, wherein said second spatial distribution comprises a uniform spatial distribution.

52. A method according to any of claims 47-51, wherein said first spatial distribution comprises a non-uniform spatial distribution.

5 53. A method of resampling comprising:
providing data in a first spatial distribution of data points;
providing a second spatial distribution of data points;
pre-multiplying said data by a diagonal density pre-compensation matrix which
includes at least one element having a negative value; and
10 resampling said data from said first spatial distribution onto said second spatial
distribution.

54. A method according to claim 53, wherein said diagonal pre-compensation matrix
comprises both positive and negative elements.

15 55. A method according to claim 53 or 54, comprising reconstructing an image from said
resampled data by applying an FT (Fourier Transform) to said data.

56. A method according to claim 55, comprising pixel-by-pixel multiplying the
20 reconstructed image by a pre-determined post-compensation matrix.

57. A method of determining a diagonal density pre-compensation matrix, comprising:
providing a first spatial distribution of data points;
providing a second spatial distribution of data points;
25 determining a first interpolation matrix for resampling data from said first spatial
distribution to said second spatial distribution;
determining a second interpolation matrix for resampling data from said second spatial
distribution to said first spatial distribution; and
determining a diagonal pre-compensation matrix which minimizes an error between an
30 identity matrix and the multiplication of the first and second interpolation matrices.

58. A method according to claim 57, wherein said diagonal pre-compensation matrix
comprises elements having negative values.

59. A method according to claim 58, wherein said diagonal pre-compensation matrix comprises both positive and negative elements.

5 60. A method according to any of claims 57-59, wherein said first interpolation matrix is generated by multiplying two or more matrices.

61. A method according to any of claims 57-60, wherein said determining a diagonal pre-compensation matrix comprises generating a set of equations.

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62. A method according to claim 61, wherein generating a set of equations comprises generating a matrix equation, which equation comprises a multiplication relationship between a plurality of matrices.

15 63. A method according to claim 62, wherein said plurality of matrices comprises a backwards interpolation matrix, a diagonal pre-compensation matrix, an interpolation coefficient matrix and a convolution matrix.

20 64. A method according to claim 63, comprising, for each element on the diagonal of said diagonal matrix, selecting only a portion of said backwards interpolation matrix.

65. A method according to claim 64, wherein said portion corresponds to portions of said backwards interpolation matrix which generate a non-zero value when multiplied by said diagonal element.

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66. A method according to claim 64, wherein said portion corresponds to portions of said backwards interpolation matrix which correspond to uniformly sampled data points within a region in k-space surrounding a data point represented by said diagonal element.

30 67. A method according to claim 66, wherein said region is circular.

68. A method according to claim 66, wherein said region is rectangular.

69. A method according to any of claims 66-68, wherein selecting comprises selecting only some of the parts of the backwards interpolation matrix which correspond to data points within said region.

5 70. A method according to any of claims 64-69, wherein said portions comprise rows.

71. A method according to any of claims 64-69, wherein said portions comprise columns.

72. A method according to any of claims 63-71, comprising, for each element on the
10 diagonal of said diagonal matrix, selecting only a portion of said convolution matrix.

73. A method according to claim 72, wherein said portion of said convolution matrix corresponds to uniformly sampled data points within a second region in k-space surrounding a data point represented by said diagonal element.

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74. A method according to claim 73, wherein said second region is circular.

75. A method according to claim 73, wherein said second region is rectangular.

20 76. A method according to any of claims 73-75, wherein selecting comprises selecting only some of the parts of the convolution matrix which correspond to data points within said second region.

77. A method of resampling data organized in a first spatial distribution of sampled data
25 points onto a second spatial distribution of resampled data points, comprising:
obtaining statistical information pertaining to the sampled data or the resampled data;
and

estimating the values of the resampled data points responsive to the obtained statistical information and to the sampled data.

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78. A method according to claim 77, wherein obtaining the statistical information comprises acquiring data containing substantially only noise and determining the statistical information therefrom.

79. A method according to claim 77 or claim 78, wherein obtaining the statistical information comprises guessing the statistical information.

5 80. A method according to any of claims 77-79, wherein obtaining the statistical information comprises estimating the statistical information from the sampled data.

81. A method according to any of claims 77-80, wherein obtaining the statistical information comprises estimating the statistical information using one or more sets of
10 previously acquired sampled data.

82. A method according to any of claims 77-81, wherein obtaining the statistical information comprises retrieving the statistical information from a table.

15 83. A method according to claim 82, wherein retrieving the statistical information from a table comprises retrieving the information responsive to one or more attributes of the data.

84. A method according to claim 83, wherein the one or more attributes comprise an identity of an organ represented by the data.

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85. A method according to claim 83 or claim 84, wherein the one or more attributes comprise a geometry of an imaged area.

86. A method according to any of claims 83-85, wherein the one or more attributes
25 comprise a determined noise level.

87. A method according to any of claims 77-86, wherein obtaining the statistical information comprises determining the statistical information based on a characteristic of an apparatus used to sample the sampled data.

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88. A method according to claim 87, wherein determining the statistical information comprises determining based on a rate of sampling and a bandwidth of the sampled data.

89. A method according to any of claims 77-88, wherein obtaining the statistical information comprises obtaining statistical information regarding the resampled data.

90. A method according to any of claims 77-89, wherein obtaining the statistical information comprises obtaining statistical information regarding the sampled data.

91. A method according to claim 90, wherein obtaining the statistical information comprises obtaining statistical information regarding a noise component of the sampled data.

92. A method according to claim 90 or claim 91, wherein obtaining the statistical information comprises obtaining statistical information regarding a signal component of the sampled data.

93. A method according to any of claims 77-92, wherein the statistical information comprises a signal-to-noise-ratio.

94. A method according to any of claims 77-93, wherein the statistical information comprises a probability density function (PDF) of the sampled data.

95. A method according to any of claims 77-94, wherein the statistical information comprises one or more statistical moments.

96. A method according to any of claims 77-95, wherein the statistical information comprises correlation information.

97. A method according to claim 96, wherein the statistical information comprises auto-correlation information.

98. A method according to any of claims 77-97, wherein estimating the values of the resampled data points comprises determining for each of the resampled data points an estimator which is a function of the statistical information, and calculating the value of the resampled data point by applying the estimator to at least some of the sampled data points.

99. A method according to claim 98, wherein the estimator comprises a Bayesian estimator.

100. A method according to claim 98 or claim 99, wherein the estimator comprises a non-linear estimator.

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101. A method according to claim 98 or claim 99, wherein the estimator comprises a linear estimator.

102. A method according to claim 98, wherein the estimator comprises a mean of a posterior
10 PDF of the resampled data.

103. A method according to any of claims 98-102, wherein the estimator is a function of a set of interpolation coefficients.

15 104. A method according to claim 103, wherein the estimator comprises an optimal linear Bayesian mean square error (MSE) estimator.

105. A method according to claim 104, wherein the estimator comprises
 $x = \mu_x + (A^H C_N^{-1} A + C_x^{-1})^{-1} A^H C_N^{-1} (b - A \mu_x)$, wherein x represents the resampled data, b
20 represents the sampled data, A represents the set of interpolation coefficients, and C_N , C_x , and μ_x represent the statistical information.

106. A method according to claim 103, wherein the estimator comprises a function of a product of an interpolation matrix multiplied by its Hermitian conjugate and by a matrix which
25 represents the statistical information.

107. A method according to claim 106, wherein the estimator comprises a function of a matrix inverse of the product of the interpolation matrix multiplied by its Hermitian conjugate and by the matrix which represents the statistical information.

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108. A method according to claim 107, wherein the estimator is of the form
 $x = (A^H C_N^{-1} A)^{-1} A^H C_N^{-1} b$, wherein x represents the resampled data, b represents the sampled

data, A represents the set of interpolation coefficients, and C_N represents the statistical information.

109. A method according to any of claims 106-108, wherein the matrix which represents the statistical information comprises a correlation matrix of a noise component of the sampled data.

110. A method according to any of claims 106-109, wherein the interpolation matrix comprises a real matrix.

111. A method according to any of claims 103-110, wherein the set of interpolation coefficients comprises interpolation coefficients suitable for resampling the second spatial distribution of data points onto the first spatial distribution of data points.

112. A method according to any of claims 98-111, wherein the estimator minimizes an estimation error criterion.

113. A method according to claim 112, wherein the estimation error criterion comprises a root mean square error criterion.

114. A method according to any of claims 77-113, wherein estimating the values of the resampled data points comprises estimating responsive to a sub-group of the sampled data points.

115. A method according to claim 114, wherein the sub-group of sampled data points of a resampled data point comprises sampled data points in a region surrounding the resampled data point.

116. A method according to any of claims 77-115, wherein estimating the values of the resampled data points comprises estimating the values of a signal component of the data at the resampled data points.

117. A method according to any of claims 77-115, wherein estimating the values of the resampled data points comprises estimating the values of a function of the data at the resampled data points.

5 118. A method according to claim 117, wherein estimating the values of the resampled data points comprises estimating filtered values of the data at the resampled data points.

119. A method according to claim 77, wherein estimating comprises solving a set of equations of the form $E\{(x_i - \sum_{m=1}^K y_{im}(b_m + \nu_m)(b_k + \nu_k))\} = 0$, wherein x_i represent the

10 resampled data, b_i represent a signal component of the sampled data, ν represents a noise component of the sampled data, and y_{im} represent the estimator.

120. A method according to any of claims 77-119, wherein the sampled data comprises medical imaging data.

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121. A method according to claim 120, wherein said medical imaging data comprises Magnetic Resonance k-space data.

122. A method according to claim 120, wherein said medical imaging data comprises CT
20 imaging data.

123. A method according to any of claims 77-122, wherein said estimating comprises estimating spatial data having dimensionality greater than one.

25 124. A method of resampling medical imaging data organized in a first spatial distribution of sampled data points onto a second spatial distribution of resampled data points, comprising:

determining at least one attribute of the source of the data; and

estimating the values of the resampled data points from the sampled data points responsive to the determined attribute.

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125. A method according to claim 124, wherein the at least one attribute comprises an attribute of the object being imaged.

126. A method according to claim 125, wherein the at least one attribute comprises an identity of a body part being imaged.

5 127. A method according to claim 125 or 126, wherein the at least one attribute comprises an age group of a patient being imaged.

128. A method according to any of claims 124-127, wherein the at least one attribute comprises an attribute of an acquisition process of the sampled data.

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129. A method according to any of claims 124-128, wherein the at least one attribute comprises an attribute of an acquisition sequence type.

130. A method according to any of claims 124-129, wherein the at least one attribute
15 comprises an attribute of an acquisition sequence parameter.

131. A method according to any of claims 124-130, wherein the at least one attribute comprises an attribute of an acquisition apparatus.

20 132. A method according to any of claims 124-131, wherein estimating the values of the resampled data points comprises selecting an estimator responsive to the determined at least one attribute.

25 133. A method according to any of claims 124-132, wherein estimating the values of the resampled data points comprises parameterically adjusting an estimator responsive to the determined at least one attribute.

134. A method according to claim 133, wherein adjusting the estimator comprises selecting parameters of the estimator from a look up table, responsive to the at least one attribute.

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135. A method of resampling data organized in a first spatial distribution of sampled data points onto a second spatial distribution of resampled data points, comprising:

providing an estimator which depends on a parameter independent of the first and second spatial distributions;

setting a value of the parameter; and

5 applying the estimator to the sampled data points to receive values for the resampled data points.

136. A method according to claim 135, wherein providing the estimator comprises selecting an estimator which minimizes an error criterion.

10 137. A method according to claim 136, wherein the error criterion comprises a weighted error criterion, the weights representing an importance of the accuracy of the values of the resampled data points.

138. A method according to any of claims 135-137, wherein providing the estimator
15 comprises selecting an estimator according to availability of statistical information.

139. A method according to any of claims 135-138, wherein setting the value of the parameter comprises selecting a value from a discrete number of possible values.

20 140. A method according to any of claims 135-138, wherein setting the value of the parameter comprises selecting a value from a continuum of possible values.

141. A method according to any of claims 135-140, wherein setting the value of the parameter comprises setting the value responsive to an attribute of the sampled data.

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142. A method according to any of claims 135-141, wherein providing the estimator comprises providing an estimator which is a function of an interpolation matrix.

143. A method according to claim 142, wherein providing the estimator comprises
30 providing an estimator which is a function of a sum of the interpolation matrix multiplied by its Hermitian conjugate and a parameter matrix.

144. A method according to claim 143, wherein the parameter matrix comprises a diagonal matrix.

145. A method according to claim 143 or claim 144, wherein the parameter matrix comprises
5 a correlation matrix.

146. A method according to any of claims 142-145, wherein applying the estimator comprises inverting the sum of the product of the interpolation matrix multiplied by its Hermitian conjugate and of the parameter matrix.

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147. A method according to claim 146, wherein inverting comprises inverting using SVD.

148. A method according to any of claims 142-145, wherein providing the estimator comprises providing an estimator which is a function of a sum of a first parameter matrix and
15 the product of the interpolation matrix multiplied by its Hermitian conjugate and by a second parameter matrix.

149. A method according to any of claims 142-148, wherein the interpolation matrix comprises a real matrix.

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150. A method according to any of claims 135-149, wherein applying the estimator comprises applying the estimator to subsets of the sampled data.

151. A method according to claim 150, wherein applying the estimator comprises applying
25 the estimator so as to receive the values of the resampled data points responsive to respective surrounding sampled points.

152. A method according to claim 150 or 151, wherein setting the value of the parameter comprises setting the parameter separately for each of the subsets of the sampled data.

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153. A method of estimating a set of MRI-related values, comprising:

acquiring a set of MRI values which are related to the estimated MRI-related values through a linear model;

determining an association matrix which defines a linear association between a sub-group of the estimated values and a sub-group of the sampled values; and

5 estimating the set of MRI related values by applying an estimating matrix to the sampled set of values, the estimating matrix being a function of the sum of a product matrix and a first parameter matrix, the product matrix being a product of the association matrix multiplied by its Hermitian conjugate and by a second parameter matrix.

154. A method according to claim 153, wherein the first parameter matrix comprises a diagonal matrix.

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155. A method according to claim 153 or claim 154, wherein the second parameter matrix comprises a unit matrix.

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156. A method according to any of claims 153-155, wherein the estimating matrix comprises a function of an inverse of the sum of the product matrix and the first parameter matrix.

157. A method according to any of claims 153-156, wherein the second parameter matrix comprises a correlation matrix representing noise added to the sampled set of MRI values during acquisition.

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158. A method according to any of claims 153-157, wherein the association matrix comprises a matrix of interpolation coefficients.

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159. A method according to any of claims 153-158, wherein applying the estimating matrix comprises applying to a subset of the set of values.

160. A method of resampling data organized in a first spatial distribution of sampled data points onto a second spatial distribution of resampled data points, comprising:

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acquiring sampled data; and
applying an optimal linear Bayesian mean square error estimator to the sampled data points so as to receive values for the resampled data points.

161. A method according to claim 160, wherein applying the estimator comprises setting arbitrarily at least one matrix of statistical data required by the estimator.

5 162. A method according to claim 161, wherein setting arbitrarily comprises assigning a diagonal matrix value.

163. A method of resampling data organized in a first spatial distribution of sampled data points onto a second spatial distribution of resampled data points, comprising:

10 applying a first estimator to a first sub-group of the sampled data points to receive values for a first sub-group of the resampled data points; and

applying a second estimator to a second sub-group of the sampled data points to receive values for a second sub-group of resampled data points.

15 164. A method according to claim 163, wherein the second estimator is different from the first estimator.

165. Apparatus for resampling data organized in a first spatial distribution of sampled data points onto a second spatial distribution of resampled data points, comprising:

20 a medical imaging receiver which acquires the sampled data;
an input interface which receives statistical information regarding the sampled data or the resampled data; and

a processor which estimates the values of the resampled data points responsive to the statistical information and to the sampled data.

25 166. Apparatus according to claim 165, comprising a memory which stores a look up table of statistical information suitable for various types of sampled data.

167. Apparatus according to claim 165 or 166, wherein the processor applies an optimal linear Bayesian mean square error estimator to the sampled data

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168. Apparatus for imaging, comprising:

a medical imaging receiver which samples a plurality of sampled data points; and

a processor which resamples the sampled data points by applying an estimator to the sampled data points, and converts the resampled data points into an image,

wherein the estimator is dependent on a parameter unrelated to the sampled data.

- 5 169. Apparatus according to claim 165, wherein the receiver comprises an MRI receiver.